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## **Abstract**

A novel Doppler spectrometer is currently being used for ion or neutral velocity and temperature measurements on the Alcator C-Mod Tokamak. The spectrometer has an  $f/\#$  of  $\sim 3.1$  and is appropriate for visible light (3500 – 6700 Å). The full width at half maximum from a line emitting calibration source has been measured to be as small as 0.4 Å. The ultimate time resolution is line brightness light limited and on the order of ms. A new photon efficient detector is being used for the setup at C-Mod. Time resolution is achieved by moving the camera during a plasma discharge in a perpendicular direction through the dispersion plane of the spectrometer causing a vertical streaking across the camera face. Initial results from C-Mod as well as previous measurements from the Compact Toroid Injection Experiment (CTIX) and the Sustained Spheromak Plasma Experiment (SSPX) are presented.

## I. Introduction

The velocity of neutrals and ions in all regions (edge and core) are important quantities to measure in the study of transport in tokamaks. An intrinsic core rotation profile, obtained from x-ray spectroscopy, is routinely measured in Alcator C-Mod plasmas without any particle or momentum sources<sup>1,2,3</sup>. This rotation seems to be related to the Low (L) to High (H) confinement mode transition<sup>4,5,6</sup> as well as to the formation of internal transport barriers<sup>7</sup>. The momentum in enhanced D-alpha and edge-localized mode-free H-modes seems to propagate in from the edge by diffusion and convection respectively<sup>8,9,10</sup>. An edge momentum source has been invoked to support a momentum diffusion convection model for the results at C-Mod. The actual measurement of the edge parameters is still underway. It should be noted that recently work done at Tokamak à Configuration Variable (TCV) has found the absence of an edge momentum source in its Ohmic L-mode<sup>11</sup>. This possible edge momentum source is still not understood. The extension of the investigation of the intrinsic core rotation to the edge is a subject of great interest.

The electron temperature around the last closed magnetic flux surface (LCFS) ranges from a few eV to a few 100 eV on the Alcator C-Mod Tokamak. The most abundant charge states in the edge plasma include, but are not limited to a few time ionized B, Ar, O as well as neutral D, and He. Visible lines fed from metastable levels are convenient for measuring Doppler width and shifts at the plasma edge to obtain the velocity and temperature, respectively. A novel high throughput Doppler spectrometer has been installed on the Alcator C-Mod tokamak for plasma rotation measurements.

Details of a previous version of the spectrometer based on a design used at the Livermore high energy electron beam ion trap (SuperEBIT)<sup>15</sup> have been presented in Ref. 16. The current version gives a single line integrated spectrum every 4 ms, with a possible instrument function full width at half maximum (FWHM) of 0.4 Å and a spectral bandpass of  $\sim 150$  Å.

Measurements with the Doppler spectrometer presented here were done at three facilities: the Compact Toroid Injection Experiment (CTIX)<sup>13</sup>, the Sustained Spheromak Plasma Experiment (SSPX)<sup>14</sup> and the Alcator C-Mod tokamak. These illustrate the utility of the instrument and the adaptations needed to observe plasma with very different time scales.

## II. Compact Toroid Injection Experiment

The Compact Toroid Injection Experiment (CTIX)<sup>13</sup> is a plasma accelerator based on the design of a Marshall gun<sup>17</sup>. Beyond a test bed for various basic plasma physics, its original purpose was to be used as a fueling mechanism for magnetic confinement devices. It is a coaxial pipe arrangement where the plasma is formed on one end between an inner and outer conductor. The plasma ring with its self-sustaining toroidal and poloidal magnetic fields is then accelerated down the pipe by a  $\mathbf{J} \times \mathbf{B}$  force. The current is flowing from the outer to the inner conductor through the plasma itself. The velocity of the compact toroid is typically 200 km/s according to a time of flight measurement of magnetic signals propagating down the gun. A typical shot lasts only 40 – 50  $\mu$ s. It was necessary to use a single frame intensified CCD to obtain spectra in 1-2  $\mu$ s increments. Fortunately, the plasma is fairly repeatable and it is possible to build a time history

progressively. First, in order to decide what impurities were present, a high resolution spectral survey covering (3600 to 6700 Å) was performed. This was done on a shot to shot basis owing to the 150 Å band pass per exposure. A spectrally rich region containing He II (4686 Å), N II (4630 Å) and O II (4649 Å) was then used for sight line integrated velocity measurements. An input fiber optic to the spectrometer was arranged to look down the barrel of the gun so as to create blue shifted spectra. One spectrum was taken every 1.5  $\mu$ s for the first 19  $\mu$ s of progressive shots. Additional, zero velocity, unshifted, reference spectra were obtained by looking transversely to the plasma motion. The line integrated average velocity data is seen in Figure 1. We note that the He II velocity peaks very early at 1.5  $\mu$ s with a maximum of  $\sim 50$  km/s. There is a second peaking at 14  $\mu$ s with a velocity  $\sim 70$  km/s. This second peaking is coincident with the plasma torus leaving the inner conductor and entering the drift section of the accelerator. There is a re-strike in the formation section of the gun at this point due to the ringing of the rail gun circuit. The maximum velocity measured by spectroscopy is much less than the 200 km/s measured from the time of flight magnetic probes. A possible explanation for the discrepancy is that as the plasma advances, the abundance of He II decreases. Photodiodes with filters for this region of the spectrum were placed along the gun transversely. It was seen that the He II signal did indeed decrease significantly as the plasma propagated down the gun. The peak electron temperatures of  $\sim 55$  eV suggests that the He nucleus is eventually bare and therefore unseen by the spectrometer. Recombination rates for He II are too small for this effect to be significant before the shot is over. This allows for the further acceleration seen by the magnetics. Also, it is significant that the other heavier impurities seem to accelerate only moderately. If this

device is to be used as a fueling mechanism one wants only the relatively light (Deuterium) fuel to be injected while leaving the heavier impurities in the gun.

### III. Sustained Spheromak Plasma Experiment

The Sustained Spheromak Plasma Experiment (SSPX)<sup>14</sup> is an alternative magnetic confinement device, which uses the naturally occurring magnetic dynamo within the plasma for the generation of the main confinement field. This removes the need of complicated and expensive toroidal field coils as on a tokamak. This also lends itself to a sustained plasma because the duration of the plasma can be potentially maintained through helicity and fuel injection. While the experimental development is less complicated than most other approaches the plasma itself being self maintained is more difficult to understand and control. The plasma discharges are typically of H and last a maximum of 3 ms. The electron temperatures and densities reach peak values of 120 eV and  $4 \times 10^{20} \text{ m}^{-3}$  respectively<sup>18</sup>. The shot was thought to be long and dense enough to allow the testing of an NMOS array of photodiodes<sup>16</sup>. A fiber optic line was connected to a telescopic view at the mid-plane of the spherical plasma chamber. Multiple spectra were taken looking radially inward and in opposite toroidal directions. The time and line integrated Doppler shifts in an O III feature around  $3759 \text{ \AA}$  were recorded. The results show that there was indeed toroidal rotation with velocities up to  $\sim 20 \text{ km/s}$  (Figure 2). This interestingly correlates in both direction and magnitude to the toroidal propagation of the  $n=1$  mode. We also measured the neutral temperature of H, which was typically a shot and space averaged value of a few eV. Unfortunately, the NMOS photodiode array was determined to have insufficient sensitivity, precluding efforts to obtain time resolved measurements.



## IV. Alcator C-Mod Tokamak

Alcator C-Mod is a compact, high magnetic field, high power and particle density diverted and shaped magnetic confinement experimental facility<sup>19,20</sup>. Typical operational parameters of C-Mod include, a major and minor radius of 0.68 and 0.22 m, a peak plasma current,  $I_p \sim 2$  MA, a maximum toroidal magnetic field,  $B_t \sim 8$  T, an electron density,  $n_e$  of order  $10^{21} \text{ m}^{-3}$ , a peak electron temperature,  $T_e$  of 5 keV, a shot duration of up to 4 s and finally up to 6 MW of available RF power. This machine is a unique test bed for the burning plasma effort. The feature most relevant to ion and neutral velocity measurements is that the external auxiliary power is from Radio Frequency (RF) antennas. This means that the plasma heating mechanism is not a source of particles or momentum. The result is a reduction in the complexity of momentum and particle transport studies. Further, the situation is very much as it would be in a working reactor where the alpha particles are the primary heating mechanism.

In 2005, a time integrated spectral survey was recorded progressively using both divertor views and toroidal views from the inner wall just outside the separatrix. The visible survey is dominated by the Deuterium Balmer series. There are available some relatively dim features from  $B^{+4}$  (4945 Å) and  $B^{+1}$  (4940 Å) that exist because of the boronization process used to reduce other impurities in the bulk plasma. The B lines are prime candidates for Doppler measurements.

Employing a Princeton Instruments PISX camera, we were able to achieve a light limited time resolution of  $\sim 30$  ms/frame for the boron features. Faster scans down to 8

ms/frame have been recorded. Unfortunately the feature(s) of interest were bright enough only for portions of the discharge. The camera is LN<sub>2</sub> cooled and has 1300x1340, 20  $\mu$ m square pixels. It has a very slow ( $\sim 1$  min for  $\sim 1$  in<sup>2</sup> chip) readout, however time resolution is achieved by moving the camera during a plasma discharge in a perpendicular direction through the dispersion plane of the spectrometer causing a vertical streak across the camera face. The time resolution is determined by the speed of the vertical motion and the vertical height of the image (typically 75  $\mu$ m). The vertical motion of the detector including the position and velocity is recorded. Multiple toroidal, poloidal and divertor views are available to fiberoptically connect to the tokamak. The data shown in Figs. 3 and 4 used a toroidal inner wall view just outside the LCFS ( $R = 42$  cm). Zeeman splitting, dominated by the two  $\sigma$  components that result from looking nearly parallel to an  $\sim 4$  T magnetic field, is present. The line fitting function for each feature is a sum of two displaced Gaussians each convolved with a single Gaussian representing the instrument function. An example fit is seen in Fig. 3. Velocity temperature and amplitude from the  $2s3d\ ^1D_2 - 2s3d\ ^1F_2$  transition in B<sup>+</sup> at 4940.38 Å, using 30 ms/frame is shown in Fig. 4. The error in the measurements includes only the statistical contribution.

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## Captions

Figure 1: Average line integrated impurity velocity vs time of He II, N II and O II from visible spectroscopy in the compact toroid plasma accelerator.

Figure 2: Average line integrated impurity velocity of O III from visible spectroscopy in the Sustained Spheromak Plasma Experiment. The rotation is clockwise from above. Opposing toroidally oriented views were chosen looking clockwise (CW) and counter clockwise (CCW) from above.

Figure 3: Representative fit of  $2s3d\ ^1D_2 - 2s3d\ ^1F_2$  from  $B^{+1}$  at  $4940.38\ \text{\AA}$ . Also included in the fit is the less intense  $B^{+4}\ n=7-6$  transition at  $4944.6\ \text{\AA}$ . Each is Zeeman split from looking nearly parallel to  $\sim 4\ \text{T}$  magnetic field lines. The features are fit using the sum of two displaced Gaussians each convolved with a single Gaussian instrument function.

Figure 4: Velocity, temperature and amplitude as a function of time for  $B^{+1}$  at  $4940.38\ \text{\AA}$  for shot 1060314012. The error bars in velocity and temperature reflect only the statical contribution (Top) Velocity in km/s. (solid) the average of the two Zeeman \_ peaks is used as the shifted position (dash) the contribution of the individual components to the Doppler shift. (Ideally they should all be the same) (Middle) Ion temperature in eV (Bottom) Amplitude in counts.

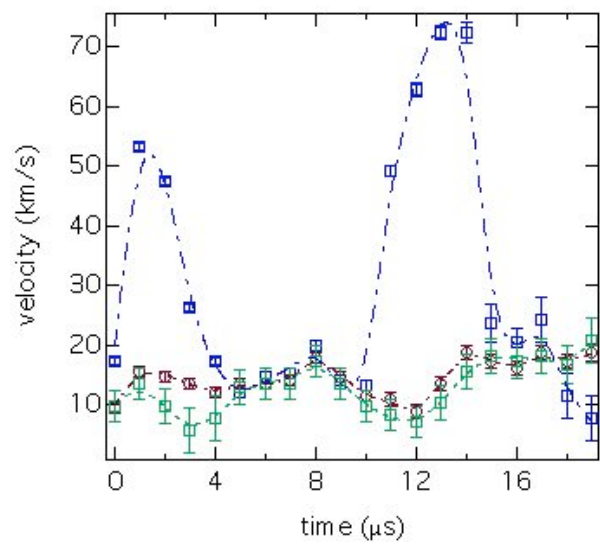


Fig1

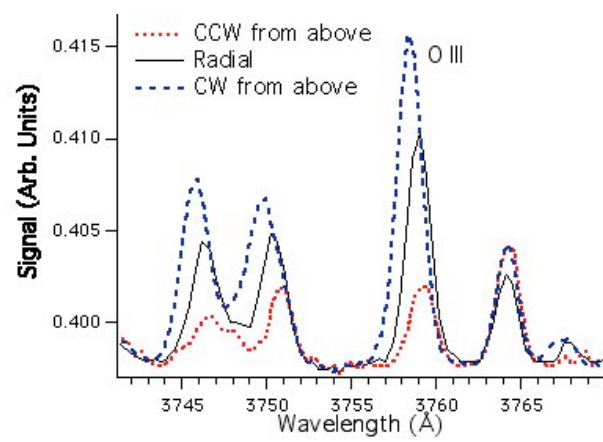


Fig2

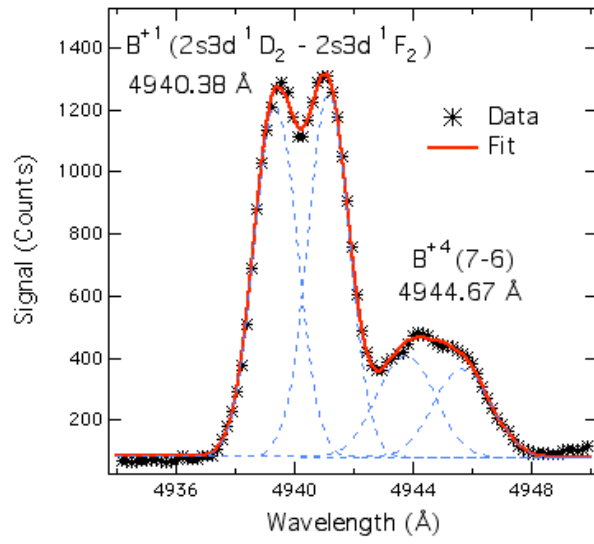


Fig 3



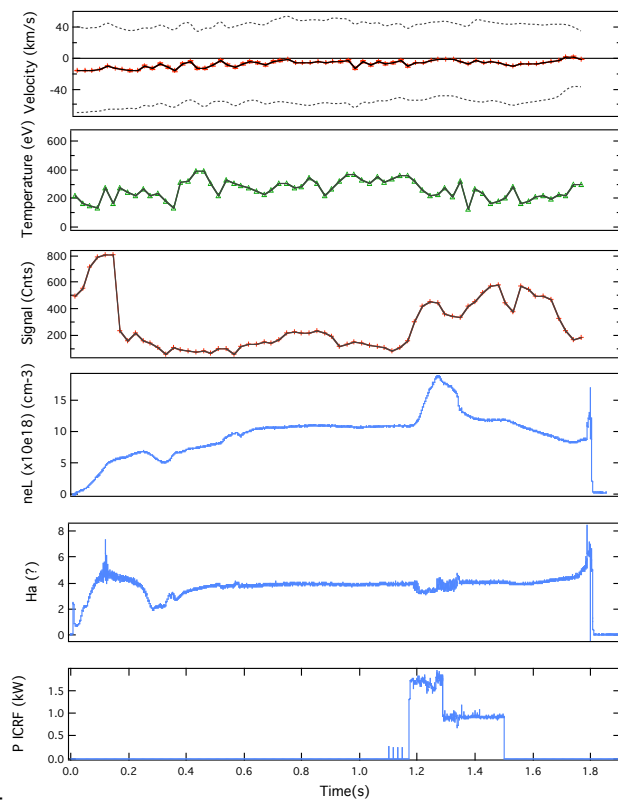


Fig 4